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USE OF MIRROR-LENS OBJECTIVES IN PHOTOGRAPHING ARTIFICIAL EARTH SATELLITES

[Following is the translation of an article by N.V.Yakovlev entitled "K voprosu o primenenii zerkal'no-linzovykh ob"yektivov dlya fotografirovaniya iskusstvennykh sputnikov zemli (ISZ)" (English version above) in Astronomicheskiy Zhurnal (Astronomical Journal) vol.37, No.3, pages 550-554.]

ABSTRACT

Data on the dimensions and main optical characteristics of a high-speed mirror-lens objective are given. The objective permits the photographing of artificial earth satellites of the sixth magnitude on film with a sensitivity of about 500 $lux^{-1} sec^{-1}$.

The photographic observation of artificial earth satellites requires optical systems possessing a high speed and resolution.

The basic demands made on such optical systems were enumerated in the Soviet[1,2] and foreign[3] literature.

The optical system must have a relative aperture on the order of 1 : 1 for a focal length of about 300-500 mm, a field of vision angle not less than 12°-15°, and a high image quality not only at the center of the field of vision but also at its edges. Of all the high-speed objectives for the above focal lengths mirror-lens objectives have the highest resolving power. Mirror-lens objectives consist of a concave spherical mirror and dioptric compensators located in front of the mirror in the parallel beam.

The following compensators which have found application in high-speed mirror-lens objectives should be mentioned:

(1) a double-lens afocal compensator;

(2) an achromatic meniscus with a retouched front or back surface;

(3) a Schmidt correcting plate mounted at the center of curvature of the mirror.

The simpler high-speed mirror-lens objectives, which consist of a concave spherical mirror and of the above compensators, when corrected for the aberration of axial points can obviously not be corrected for the aberration of a broad oblique beam for focal distances on the order of 500 mm and field of vision angles of about 15°.

To improve the quality of the image in the whole field, simpler objectives have to be made more complex.

A typical example of such a complex construction of an optical system intended for photographing artificial earth satellites is the system worked out by I. Becker.[3]

Figure 1 illustrates the principle of this objective. The objective consists of three lenses fulfilling the parts of a compensator and of a concave spherical mirror.

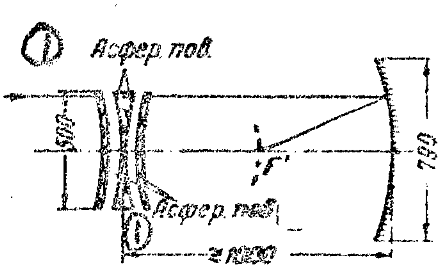

Fig. 1

1-Aspherical surface

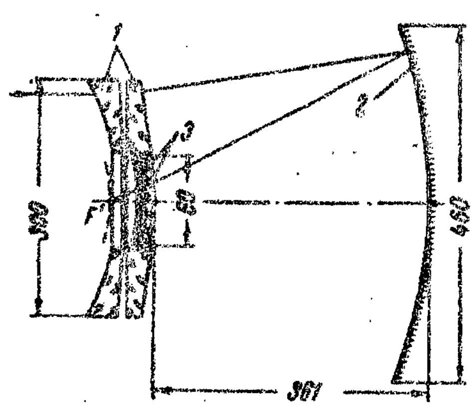

Fig. 2

The central lens is located at the center of curvature of the mirror, the other two are placed symmetrically about the central lens.

All inner compensator surfaces are aspherical, the second and the fifth and also the third and the fourth being equal.

Compared with the classical Schmidt system, this system has a larger residual chromatism.

To correct this chromatism and to decrease the secondary spectrum, the compensator lenses are made of uncommon types of glass: the central lens is made of Schott K-14, and the outer lenses are made of Schott KzFS-2. The focal length of the objective is 500 mm; the diameter of the spherical mirror is about 790 mm; the focal surface is spherical with a radius of curvature of approximately 508 mm.

The residual aberrations are small. According to the author, about 80% of the rays from the ultraviolet portion of the spectrum up to the deep red portion of the spectrum are focused in a 20-μ circle of confusion for all points in a 30° field.

It is known that the construction of a very precise optical system with large diameters and aspherical surfaces is an extremely difficult and painstaking task (reference 4).

In this connection, the construction of a high-speed high-quality optical system employing only spherical surfaces could speed up the construction of photographic cameras needed for photographing artificial earth satellites.

Below we describe a high-speed mirror-lens objective* whose optical characteristics we believe correspond to the essential requirements.

The optical diagram of the objective is shown in Fig.2.

The objective consists of a spherical concave mirror and of two dioptric components of negative power, 1 and 3, placed in front and behind (with respect to the path of the light) the spherical mirror. All refracting surfaces of the system are spherical.The dioptric component 1 is located in front of the spherical mirror between its center of curvature and its vertex in a

* 1.Author's certificate No.121262 for a claim of December 14, 1957.

2.Author's certificate No.122625 for a claim of July 8, 1958.

parallel beam and consists of two lenses located side by side. The lenses are made of various types of glass: crown and flint. The dioptric component 3 located behind the mirror (with respect to the path of the light) is also placed between the center of curvature of the mirror and its vertex and consists of two adjacent lenses. These lenses are also made of crown and flint glass. The focal lengths of each component are not less than three focal lengths of the whole objecve. The objective permits a very good correction of the chromatism of position and of the magnification of the spherical aberration, of coma, and astigmatism.

The possibility of a very good correction of the aberration of a broad oblique beam (spherical aberration and coma) must be noted. The curvature of the field is not corrected.

As an example we cite the optical characteristics and residual aberrations of one such system. The focal length was 300 mm, the relative aperture 1:1, and the angle of the field of vision was 15°, which corresponds to a focal surface with an approximate diameter of 78 mm. The last section of the objective was 31 mm.

The radius of curvature of the spherical focal surface was +230 mm (sphere of comparison). The objective was corrected for the D line and achromatized for the F and C lines.

The objective had the following residual aberrations*:

1. The transverse spherical aberration for axial points (circle of confusion) did not exceed 10 μ.

2. The coma for field points 26 mm from the image center (the region of the field of vision) did not exceed 5 μ, and for field points 39 mm distant (field edge) it did not exceed 12 μ.

3. The diameter of the circle of confusion for the above region of the field of vision did not exceed 14 μ.

4. For the edge of the field of vision the circle of confusion had in the meridional plane an elongation of about 50 μ, and in the sagittal plane an elongation of about 25 μ; about 80% of the rays of an oblique D beam were focused in a 25-μ circle of confusion.

5. The astigmatism of the edge of the field of vision did not exceed 11 μ.

6. The mean curvature of the image for the edge of the field of vision with respect to the Gaussian

* The aberrations are given relative to the sphere of comparison.

plane was 3.285 mm, and with respect to the sphere of comparison it was 0.086 mm.

7. With regard to chromatism we point out that for the edge of the field of vision the rays of a broad meridional beam from the F to the C line are focused in a 60-μ section.

8. For axial points about 80% of all rays from F to C were focused in a circle of confusion the diameter of which did not exceed 40 μ.

9. The maximum wave aberration for the D line (λ = 0.5893 μ) did not exceed in absolute magnitude 0.075 μ. Below we have listed the values of the residual wave aberrations (h_y) in microns and in fractions of the wavelength ($h_y : \lambda$) for axial points for varicus aperture regions. The notation for the wave aberration is in accordance with reference 4. The calculations were carried out according to formula (5).

h_1, мм	h_y, μ	$h_y : \lambda$	h_y^0, μ	$h_y^0 : \lambda$
0.00	0.00000	0.0000	0.00000	0.0000
72.5	—0.01471	—0.0249	—0.04413	—0.0749
101.5	0.05845	0.0992	—0.00023	—0.0004
124.7	0.15261	0.2590	0.08254	0.1061
145.0	0.05110	0.0867	—0.07280	—0.1235

The wave aberrations h_y and $h_y : \lambda$ listed in the Table are calculated under the condition that the center of the sphere of comparison coincides with the paraxial focus of the objective. If the center of the sphere of comparison is displaced from this position along the optical axis by 0.001 mm with respect to the path of the light, we obtain new values of the wave aberrations denoted in the Table by $\overset{0}{h}_y$ and $\overset{0}{h}_y : \lambda$.

As can be seen from the Table, in the new plane of setting $(\overset{0}{h}_y : \lambda)_{max}$ does not exceed one eighth of a wavelength.

To compare the above objective with others it is sufficient to say that in high-speed objectives employed in practice the wave aberrations often exceed 5 - 8 wavelengths.[8]

The well-known objectives of the "Industar" type with focal lengths on the order of 200 mm and a relative aperture of 1 : 4.5 have a wave aberration of 2 - 3 wavelengths in the plane of the best setting.

In summing up the aberration characteristics of the objective it must be pointed out that the meniscus system of D.D. Maksutov which has found wide employment in astronomy cannot be completely corrected for a 1 : 1 relative aperture of the objective, a focal length of the order of 300 mm, and a field of vision angle of 15° without the use of aspherical surfaces.[7]

For the calculation of the objective optical glass of Soviet make was employed (GOST 3514 - 57).

In the objective whose residual aberrations have been listed above the following makes of glass were used for the lenses of the first dioptric component: BK10 for the first lens (with respect to the path of light), and TFZ for the second lens; for the lenses of the second dioptric component F4 and TK21 glass was used.

It should be noted that the optical characteristics of the described objective can be duplicated employing in the first and second dioptric components various glass combinations, that is there exists a certain freedom in the choice of the glass with the desired physicochemical characteristics.

We should in particular dwell on the question of the distribution of the intensity of illumination on the focal surface ("the photometric error in the field").

It is known that in optical systems even in the absence of vignetting of oblique rays by the lens mounting and with specially placed blinds the illumination of the focal surface at the center of the surface is more intense than at its edges, and this difference increases with the angle of the field of vision.

If the object is a uniformly bright plane perpendicular to the optical axis, then in the first approximation (in the absence of aberration in the pupils) it can be assumed that in objectives with a plane focal surface the illumination of the image of a point is proportional to the fourth power of the cosine of the angle of the field of vision. The special feature of the objective which we have considered consists in that it has an annular exit pupil and the image is located on a sphere of 230 mm radius.

The ratio of the illumination at any point in the field of vision (E') and the illumination at the center of the field of vision (E_0') can be calculated from the expression

$$\frac{E'}{E_0'} = \frac{\int\limits_{r=a}^{r=b} r\,dr \int\limits_{\varphi=0}^{\varphi=2\pi} \frac{\cos i_2' \cos (L, Y)}{L^2}\, d\varphi}{\pi\,(\sin^2 u_b' - \sin^2 u_a')},$$

where a and b are the inner and outer radii of the ring. The remaining notation is the same as in the book by A.I.Tudorovskiy.[8]

Numerical integration, the technical details of which are omitted, yielded the following results:

1) for the region of the field of vision within a radius of 26 mm, $E':E_0' = 0.999$

2) for the edge of the field of vision, $E':E_0' = 0.991$.

Owing to vignetting, i.e. to the secondary shading of oblique rays by the lens mounting, the ratio $E':E_0'$ for the region of the field of vision reduces to about 0.97; for the edge of the field it reduces to 0.951.

We will estimate the efficiency of the described objective as a photographic telescope. In recording a moving point object (an artificial earth satellite) the following relations hold

$$t = \frac{3438 \cdot d}{\omega \cdot f'}, \qquad (1)$$

where t is the exposure time in seconds, $d = d_1 + d_2$ is the maximum track width in millimeters, d_1 is the diameter of the circle of confusion of the image of a point, d_2 is the diameter of the circle of confusion of the emulsion, f' is the focal length, ω is the angular velocity of the object in minutes of arc per second,

$$l = d\frac{T}{t}, \qquad (2)$$

where l is the length of the trace (track) corresponding to a time T, and T is the time lag of the shutter, where $T \geqslant t$

$$S = \frac{\omega}{E} \cdot \frac{4}{3438 \cdot \pi \cdot \tau} \cdot \frac{d \cdot f'}{D^2}, \qquad (3)$$

where S is the sensitivity of the emulsion in $lux^{-1} sec^{-1}$, E is the illumination due to the moving object at the first surface of the objective in lux, τ is the transmission coefficient of the system taking into account the losses due to reflection, absorption, and screening, D is the diameter of the entrance pupil of the objective in mm. For an objective free of aberrations $d = d_2 = 30\,\mu$, that is it is equal to the diameter of the circle of confusion of a highly sensitive emulsion.

We will approximately determine the limiting stellar magnitude of the satellite which leaves a track on the emulsion.

We assume in place of the satellite a specularly reflecting sphere with a diameter of 50 cm, whose photovisual stellar magnitude, distance from the observer, and angular velocity are given in the article of G.Henize.[3]

For a satellite of stellar magnitude 5.7, $\omega = 88\ sec^{-1}$, the illumination at the surface of the earth (with account of the atmospheric effect) is approximately 10.55×10^{-9} lux.

The minimum width of the track is preliminarily determined by the well known method of reference 4. For a Panchrome type photographic layer and the center of the field of vision $d = 30$ to 40μ, for the type of objective which we are considering

$$D = 300 \text{ mm}, \ f' = 300 \text{ mm}, \text{ and } \ \tau \cong 0.7.$$

A calculation using formulas (1), (2), and (3) yields approximately

$$t = 1/250 \text{ sec}, \ 1 = 7.5 \cdot T \text{ mm}, \ S = 440 \text{ lux}^{-1} \text{ sec}^{-1}.$$

For a satellite of stellar magnitude 7.2, $E = 2.64 \times 10^{-9}$ lux, $\omega = 42 \text{ sec}^{-1}$, the calculation yields

$$t = 1/122 \text{ sec}, \ 1 = 3.68 \cdot T \text{ mm}, \ S = 840 \text{ lux}^{-1} \text{ sec}^{-1}.$$

Thus the use of highly sensitive film with a sensitivity of about 500 could make it possible to photograph with the above objective satellites of the sixth magnitude.

In conclusion, the author considers it his pleasant duty to express his gratitude to M.A. Shesmintsev for his interest in and attention to this work.

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